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A New Size Reduction Method for Radial Line Slot Array (RLSA) Antennas

Teddy Purnamirza[1, 2], Muhammad Soleh[1], Asmarita[1], Imran M. Ibrahim[3], Depriwana Rahmi[4]

Abstract – *A new size reduction method was introduced in this study for the radial line slot array (RLSA) antenna with the effects of the cutting used on antennas' performance discussed to analyze the possibility of the method's implementation. Moreover, the RLSA model and its cut version were designed, simulated, and fabricated to verify the method and its simulation, after which their performances were measured in terms of gain, S_{11}, and bandwidth. The analysis of the simulation and results showed the method has the ability to minimize antenna size by up to four times while maintaining its gain which was observed to have decreased by only approximately 50%. The other good effect of the method is the wider bandwidth of the antenna which was estimated to be 0.2 GHz.*

***Keywords**: Radial Line Slot Array, RLSA, Small RLSA Antenna, Size Reduction Method*

I. Introduction

Radial Line Slot Array (RLSA) antennas were originally intended and successfully developed for satellite broadcast applications, and were big in size [1]-[4]. Due to their success, researchers tried to minimize this size for use in small antenna applications [5]-[9].

However, this effort was constrained for years due to high signal reflection problems in these small RLSAs [10]. Several studies have been conducted to overcome this problem. For example, in 1990, Hirokawa [11] introduced a matching slot technique to dispose the power remaining at small RLSA perimeters to reduce reflections, and Akiyama [12] was also reported to have used the same technique. However, this method is believed to only have the capability to dispose the power remaining at the antenna perimeters without contributing to antenna gains. In 2004, Zagriatski used a long slot technique to maximize the power radiation through the slots to reduce its reflections from small RLSA perimeters [8]. This method was also observed to have the ability to lessen antenna gain while reducing the reflection coefficient mainly due to its inability to radiate focused power. In 2008, Islam constructed RLSA antennas using a Flame Retardant (FR4) as cavity materials [13]. These antennas were small with a radius of 75 mm and have been successfully used in UTM's bridges. However, several defects were observed during the construction process such as overlap slots, a loss due to the gluing of some layers of FR4 boards, and FR4 material loss. These all result in low gain at approximately 8 dB and narrow bandwidth of 75 MHz.

In 2008, Imran developed RLSA antennas with 26 dBi gain and they were successfully implemented for point-to-point Wi-Fi routers [14]. This design used the beam squint technique and this is observed to be the same with what is used to design RLSA antennas for satellite applications. This, therefore, means the 650 mm diameter of this antenna is still too large to be applicable in small Wi-Fi devices. Another study conducted in 2012 by Purnamirza employed three cavity layers and these include one polypropylene and two FR4 layers to enable the reflected power eliminating itself [15]. Despite the use of affordable FR4 material for the antenna, the fabrication was more complex due to the need to align the three layers with high precision. In another study, Purnamirza introduced extreme beam squint technique to efficiently radiate power through slots, which significantly reduces power reflections [16]. This also led to the successful implementation of this technique to design several small Wi-Fi RLSAs for market needs [17]-[22].

Moreover, Koli recently developed a small aperture RLSA for 11 GHz frequency [23]. This research continues the development of small RLSA antennas by proposing a size reduction method to produce smaller RLSAs while maintaining adequate performance. The process involved first optimizing the slots' position by putting them as close together as possible in the radiating area of antennas. This was achieved by designing the antennas using high beam squint values greater than 60°.

Fig. 1(a) shows an antenna designed using 80° to have produced a concentrated and vacant slot area. The second step involved theorizing the possibility of minimizing the antenna's size by cutting it and retaining only the concentrated slots area as a new, smaller antenna, as depicted in Fig. 1(b).

The research discusses the possibility of cutting RLSA antennas in order to minimize their size. This started by theoretically studying the effect of cutting on an antenna's performance in Section II.

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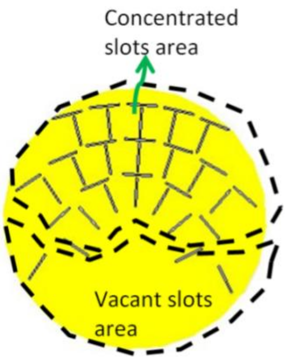


(a)

(b)

Figs. 1. (a) Designed result using high beam squint values (b) cut antenna, which is four times smaller

This was followed by the design and simulation of an ordinary RLSA antenna model to verify the developed theory as described in Section III. The proposed method was also used to produce a cut version of the ordinary model which was four times smaller and they were both measured. Finally, in Section IV the simulation and measurement results were analyzed, and conclusions were drawn.

II. The Effects of Cutting

II.1. Negative Effects

The power flow in RLSA antennas is normally perfect in a radial direction as depicted in Fig. 2(a). Several negative effects have, however, been attached to cutting RLSA antennas and these include power leakage along the cutting line and a disturbance of power flow direction within the antennas as shown in Fig. 2(b). These further influence the antenna's performance in terms of gain, reflection coefficient, and radiation pattern [24], [25].

The power leakage lessens the gain and disturbs the radiation patterns by escaping from the cutting line rather than its slots. The reflection coefficient, however, reduces as the power leakage at the antenna's perimeter and the cutting line escapes. Moreover, the disturbance of the power flow direction also lessens the gain because it is required to be in a perfect radial direction to produce optimum gains.

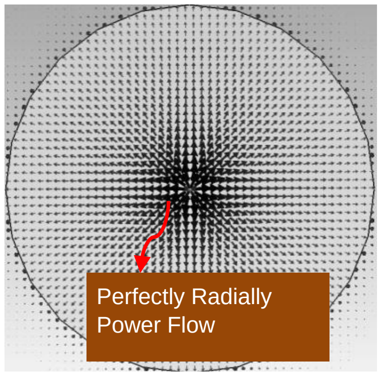
II.2. Positive Effects

Several positive effects of cutting RLSA antennas were also observed in addition to the reduction in size and these include denser slots and higher power density [24], [25]. Figs. 1(a) and (b) show the cut RLSA antenna to have denser slots than the full circle and this has the capability to radiate more power to lessen the remaining reflected power at the antenna's perimeter, thereby improving the reflection coefficient. Another side effect of cutting is the increase in power density and this was observed to be approximately four times more in a quarter-cut than in a full circle RLSA. This was associated with the flow of all the power launched by the feeders to the slots in the quarter-cut but, in the full, some were observed to be flowing to vacant areas without any contribution to the gain as shown in Fig. 2(a). The higher power density in the quarter-cut is also expected to improve the reflection coefficients and widen the bandwidth since more power escapes from the slots compared to those of the full. Both the negative and positive effects discussed in subsections II.1 and II.2 compensate each other in influencing the performance of the cut antenna. Due to the inability to manually calculate these effects, they were analyzed by simulating the RLSA antenna and its cut model. The results are discussed in sections III and IV.

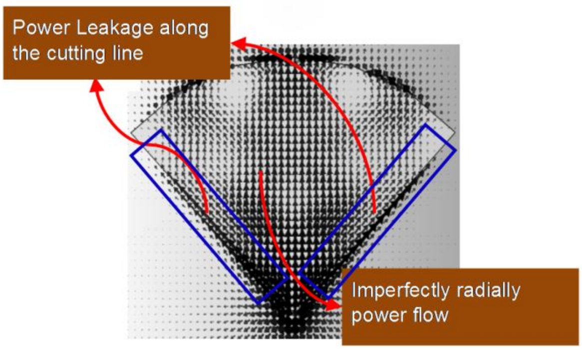
III. Antenna Models

A full antenna model was designed to verify the effects of the cutting process discussed in Section II by using a high beam squint value of 87° to concentrate the slots in a certain area of the antenna's radiating element.

The model then was cut to produce a smaller quarter-cut RLSA model.

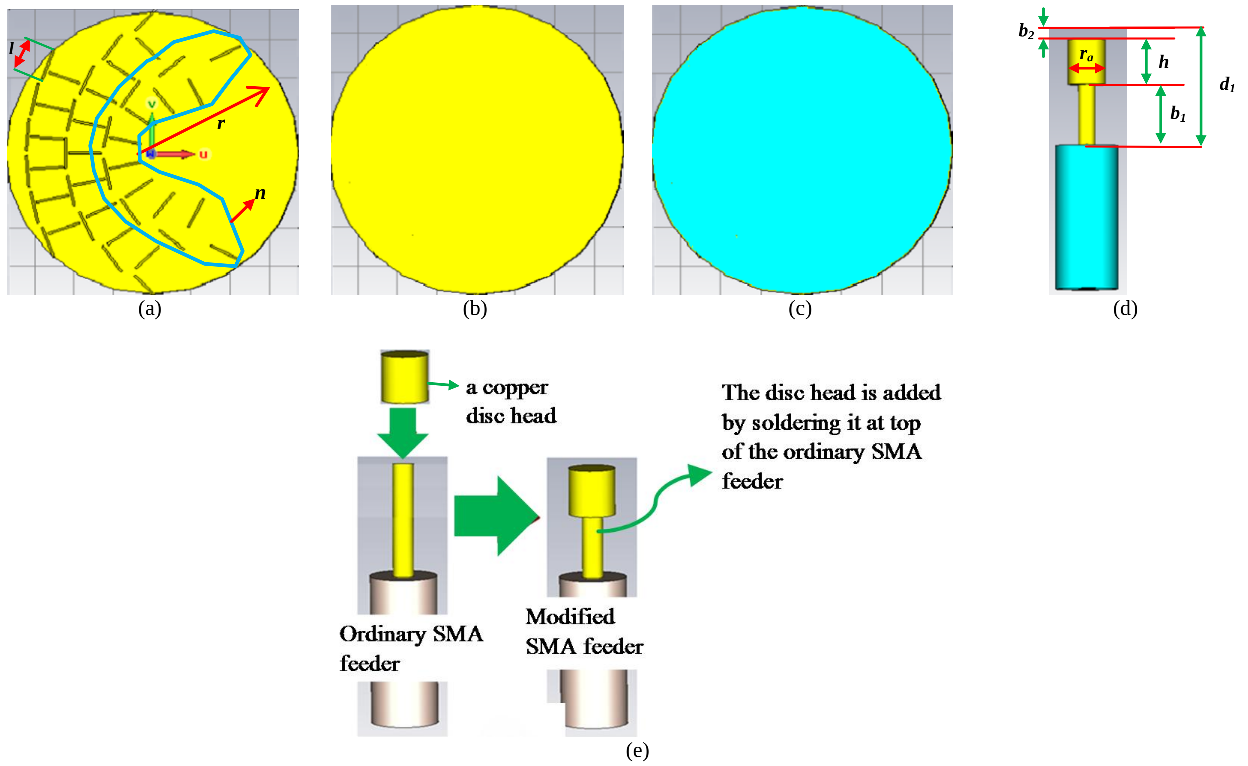


(a)

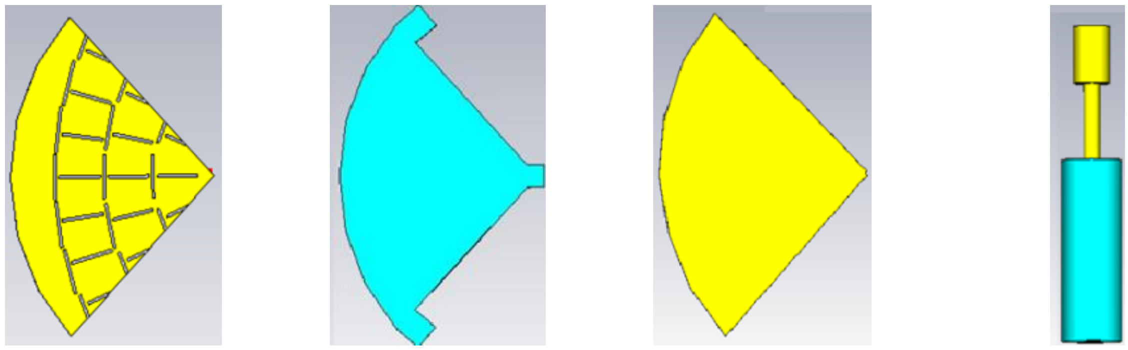


(b)

Figs. 2. Power flow within (a) full normal antennas (b) Cut antennas [25]



Figs. 3. Model of a full circle RLSA (a) radiating element (b) cavity (c) background (d) parameters of feeder (e) Modification process of feeder [20]



Figs. 4. Model of a quarter-cut RLSA (a) radiating element (b) cavity (c) background (d) feeder

The model was structured in three layers and these include a radiating element made of copper at the top, a cavity made of polypropylene in the middle, a background made of copper on the back, and a modified SMA feeder at the center, as depicted in Figs. 3 and 4 for a full circle and quarter-cut RLSA, respectively. The SMA feeder was modified by adding a disc head to an ordinary SMA feeder as illustrated in Fig. 3(e). The difficulty in drawing the antenna structure manually, especially the slots, led to the development of a computer program to draw the models' structures faster and more accurately.

All the design parameters embedded in the computer program are listed in Tables I and II, for the antenna and the feeder, respectively, while Figs. 3(a) and (d) depict their respective definitions.

Several equations were used in the computer program to calculate the inclination angle of the slots' pairs (Eq. (1) and Eq. (2)), their positions (Eq. (3) and Eq. (4)), the distance between them (Eq. (5) and Eq. (6)), and their length (Eq. (7)) [1], [2]. Table III lists the definitions of the slots pairs' parameters in all the equations while Figs. 5 were used to explain them:

$$\theta_1 = \frac{\pi}{4} + \frac{1}{2}\left\{\arctan\left(\frac{\cos(\theta_T)}{\tan(\emptyset_T)}\right) - (\emptyset - \emptyset_T)\right\} \quad (1)$$

$$\theta_2 = \frac{3\pi}{4} + \frac{1}{2}\left\{\arctan\left(\frac{cos(\theta_T)}{\tan(\emptyset_T)}\right) - (\emptyset - \emptyset_T)\right\} \quad (2)$$

$$\rho_1 = \frac{(n - 1 + q - 0.25)\lambda_g}{1 - \xi\sin\theta_T\cos(\phi - \phi_T)} \quad (3)$$

$$\rho_2 = \frac{(n - 1 + q + 0.25)\lambda_g}{1 - \xi\sin\theta_T\cos(\phi - \phi_T)} \quad (4)$$

where $\xi = \frac{1}{\sqrt{\varepsilon r_1}}$.

$$S_\rho = \frac{\lambda_g}{1 - \xi \sin\theta_T \cos(\phi - \phi_T)} \tag{5}$$

$$S_\phi = \frac{2\pi\lambda_g}{\sqrt{1 - \xi^2 \sin\theta_T{}^2}} \frac{q}{p} \tag{6}$$

$$L_{rad} = (4.9876 \times 10^{-3}\rho)\frac{12.5 \times 10^9}{f_0} \tag{7}$$

IV. Results and Analysis

The antenna models designed in Section III were simulated and fabricated as shown in Figs. 6 and 7.

Moreover, the radiation pattern, S_{11}, and the gain of the fabricated models were measured using an anechoic chamber and a network analyzer as indicated in Figs. 8.

Figs. 9 show the response of S_{11} for both the measurements and simulations, and the quarter-cut was observed to have a wider bandwidth and deeper S_{11} than the full circle due to the effect of higher power density it contains.

TABLE I
DESIGN PARAMETERS OF THE FULL RLSA ANTENNA [15], [16]

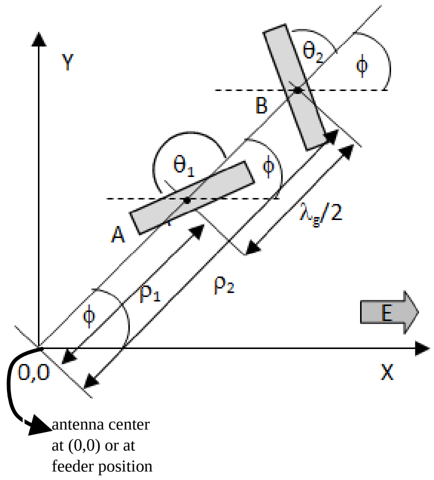
Parameters	Symbols	Values
Center frequency	f	5.8 GHz
Wavelength inside the cavity	λ_g	33.88 mm
Slot length	l	0.5λg
Slot width	w	1 mm
Antenna radius	r	85 mm
Cavity thickness	d_1	8 mm
Thickness of the radiating element and background	d	0.08 mm
Permittivity of the cavity	εr_1	2.33

TABLE II
DESIGN PARAMETERS OF THE FEEDER [15], [16]

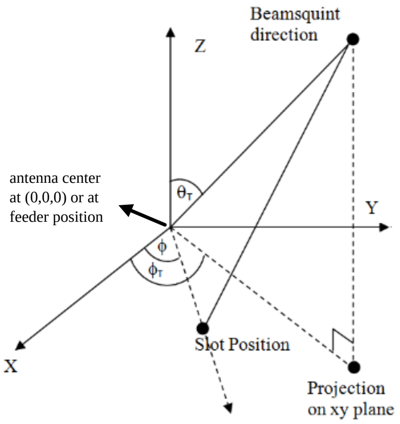
Parameters	Symbols	Values
Height of the disc	h	3 mm
Radius of the disc	r_a	1.4 mm
Lower air gap	b_1	4 mm
Upper air gap	b_2	1 mm
Material of the disc		Copper
Type of feeder		SMA Feeder

TABLE III
DESIGN PARAMETERS OF THE SLOTS PAIRS [1], [2]

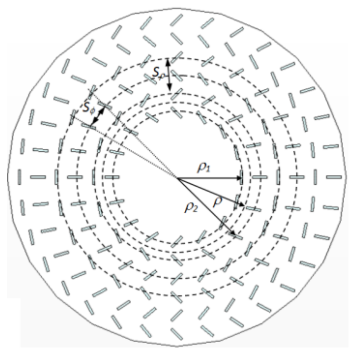
Parameters	Symbols
Inclination angle of Slot 1	θ_1
Inclination angle of Slot 2	θ_2
Beam squint angle in the elevation direction	θ_T
Azimuth angle of Slot 1 and Slot 2 position	ϕ
Beam squint angle in azimuth direction	ϕ_T
Distance of a slot 1 from the center point of antennas	ρ_1
Distance of a slot 2 from the center point of antennas	ρ_2
Number of slot pairs in the first ring	n
Integer numbers (1, 2, 3…) that express the distance of innermost ring from the center of antennas	q
Distance between two adjacent unit radiators located in two different rings (distance in the radial direction)	S_ρ
distance between two adjacent unit radiators in the same ring (distance in azimuth direction)	S_ϕ



(a)



(b)



(c)

Figs. 5. (a) Slots pairs along with all parameter in x-y plane (b) slots positions and their relations to beam direction in x-y-z (c) distance between slots in radial and azimuth directions [1], [2], [24], [25]

It was also associated with the effect of power leakage, which reduces the S_{11}, in accordance with the explanation in Section II.2.

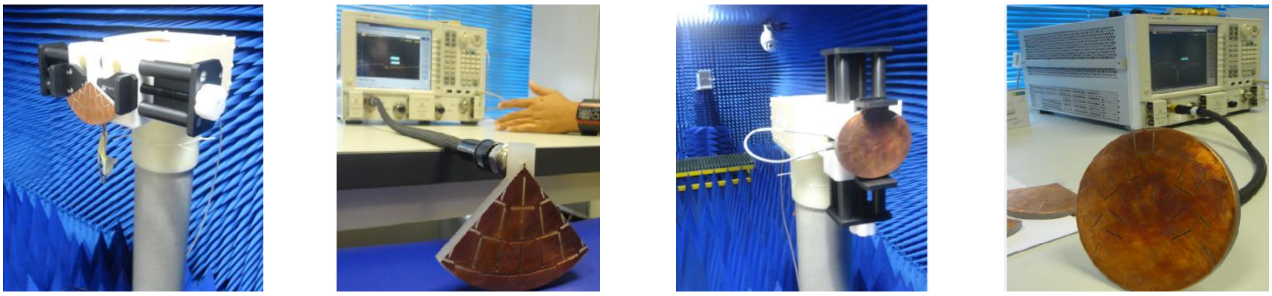
The results showed it is possible to minimize antenna sizes up to four times for cut RLSAs and that it has additional benefits in the form of widened bandwidth at 0.2 GHz and lower reflections. Figs. 10 show the radiation pattern for both the measurements and simulations. The quarter-cut was recorded to have 11.5 dB gain which is about 3 dB lower than the full circle.

(a) (b) (c)

Figs. 6. Fabricated model of quarter-cut RLSA (a) whole antenna (b) background (c) feeder

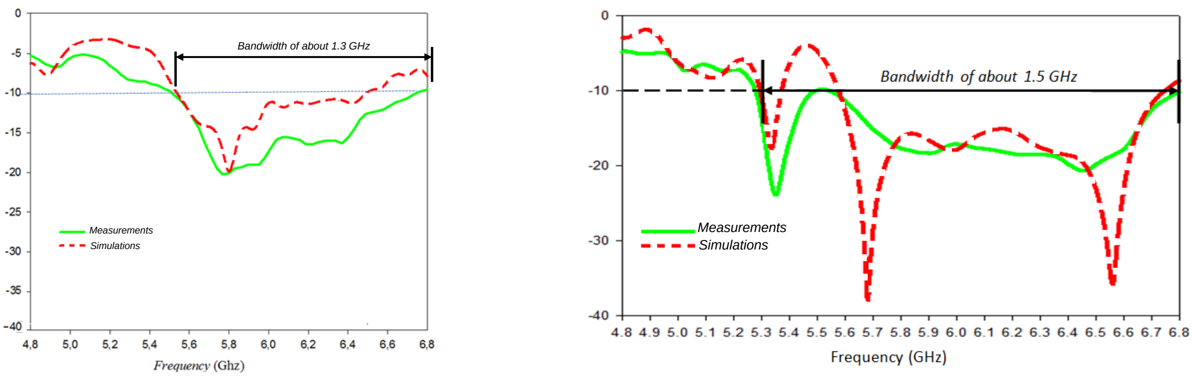
(a) (b) (c)

Figs. 7. Fabricated model of a full circle RLSA (a) radiating element (b) background (c) cavity



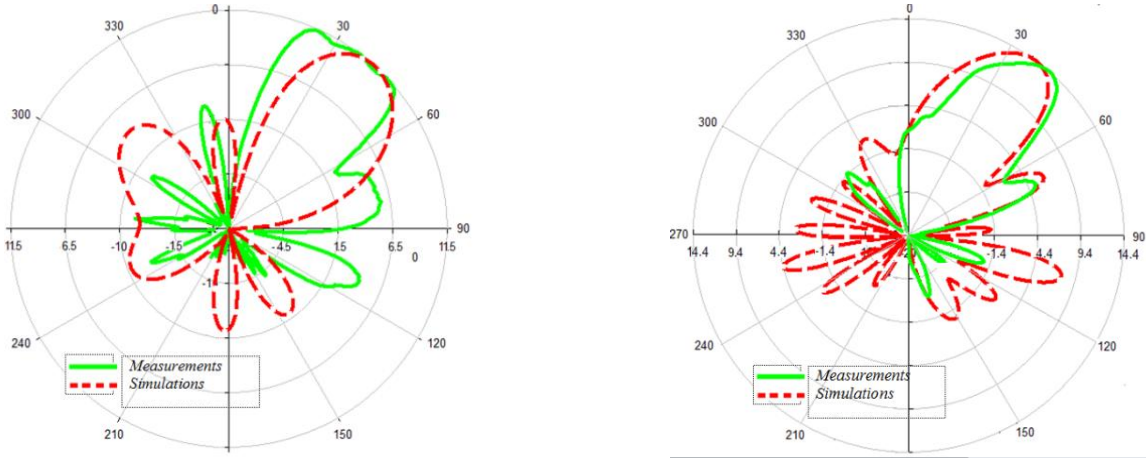
(a) (b) (c) (d)

Figs. 8. Measurement of (a) quarter-cut RLSA in an anechoic chamber (b) quarter-cut RLSA connected to a network analyzer (c) full circle RLSA in an anechoic chamber (d) full circle RLSA connected to a network analyzer



(a) (b)

Figs. 9. Measurement and simulation results of S_{11} for (a) full circle RLSA (b) quarter-cut RLSA



(a) (b)

Figs. 10. Measurement and simulation results of the radiation pattern of (a) full circle RLSA (b) quarter-cut RLSA

Theoretically, since the size of the quarter-cut is four times smaller than the full, it is expected to have approximately 6 dB (four times) gain lower than the full circle RLSA. However, the effects of denser slots and higher power density were observed to be more dominant in the quarter-cut, as discussed in Section II, than the effects of the power leakage, which led to the production of a higher gain. Therefore, it was concluded that it was possible to reduce the antenna's size by up to four times and still maintain its gain, which decreased only approximately by 50%. Finally, Figs. 9 and 10 show the simulation results corresponding with those recorded from the measurement and this means the proposed method was verified. The slight difference between the results is due to inaccuracy in fabricating the prototypes, especially in combining the radiating element, cavity, and background in an accurate parallel position.

V. Conclusion

The potency of the cutting method to realize small RLSA antennas at a frequency of 5.8 GHz, which had been limited for years due to the problem of high reflection, was shown in this study. This method is expected to be a significant step in producing small RLSA antennas with sufficient gains for small devices such as point-to-point Wi-Fi routers. The antenna designed in this research was low profile just like microstrip antennas but better due to its high gain and efficiency. Therefore, it is possible to use it as an alternative for microstrip antennas for devices with a 5.8 GHz frequency. Future investigation is required to determine the ability of this method to produce small RLSA antennas for other frequency bands and other antenna radii. In addition, the maximum size to be cut using this method also needs to be studied because a higher size of an antenna produces a greater effect of power leakage in lowering gains. Furthermore, there are other shapes apart from the quarter circle discussed in this study. Further research is recommended to be extended to these shapes such as one-third circles as well as semicircular shapes and compare their performances.

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Authors' information

[1]Department of Electrical Engineering, Faculty of Science and Technology, Universitas Islam Negeri Sultan Syarif Kasim, Indonesia.

[2]Tuanku Tambusai Telecommunication Centre, Universitas Islam Negeri Sultan Syarif kasim, Indonesia.

[3]Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Malaka, Malaysia.

[4]Department of Mathematic Educations, Faculty of Educations and Teachers Training, Universitas Islam Negeri Sultan Syarif Kasim, Indonesia

T. Purnamirza was born in Pekanbaru Indonesia on 30th October 1974. He received his bachelor degree from STTTelkom (currently Universitas Telkom) in 2000. He received his master and doctoral degree from UTM Malaysia, both in electrical engineering, in 2005 and 2013, respectively. He joined Informatic Engineering Department UIN Suska in 2000. From 2000 to 2003, he was head of informatics laboratory. He joined Electrical Engineering Department UIN Suska in 2003. From 2005 to 2007, he was head of computer laboratory. From 2007 to 2010, he was head of Electrical Engineering Department in UIN Suska. From 2013 to 2018, he was vice dean for academic affairs and institution development at Faculty of Science and Technology UIN Suska. He is now serving as associate professor in UIN Suska. He has published three books, one chapter, fifteen journal papers and four conference papers. His research interests are antennas and propagations.

M. Soleh was born in Siak, Riau, Indonesia on April, 12nd 1994. He received his bachelor degree from Universitas Islam Negeri Suska Indonesia in electrical engineering in 2016. His research interests are antennas and propagations.

Asmarita was born in Benayah, Riau, Indonesia on January, 10th 1995. She received her bachelor degree from Universitas Islam Negeri Suska Indonesia in electrical engineering in 2016. Her research interests are antennas and propagations.

I. M. Ibrahim was born in Kedah, Malaysia on 23rd June 1976. He received his bachelor degree, master and doctoral degree from UTM Malaysia, all in electrical engineering, in 2000, 2005, and 2016, respectively. He is now serving as a Senior Lecturer in UTeM. He has published more than 30 journals and conference papers. His research interests are antennas and propagations. Dr. Imran is a member of IEEE Malaysia and Institute of Engineers Malaysia.

D. Rahmi was born in Pasir Pangaraian, Riau, Indonesia on 6th March 1981. She received his bachelor degree and master degree from Universitas Riau and UTM Malaysia in 1999 and 2015, repectively. She joined Mathematic Education Department UIN Suska in 2006. She is now serving as senior lecturer in UIN Suska. She has published four books, eight journal papers and 4 conference papers. Her research interests are probability and statistics.